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ELECTRON TUBE AND MICROWAVE LABORATORY

THE LOW DENSITY PLASMA SHEATH IN CYLINDRICAL GEOMETRY

by

Jerald V. Parker

Technical Report No. 19

Nonr 220(13)

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A REPORT ON RESEARCH CONDUCTED UNDER

CONTRACT WITH THE OFFICE OF NAVAL RESEARCH

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The Low Density Plasma Sheath in Cylindrical Geometry

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Recently Kino and Self[1] have solved for the electron density and potential in a low density (long mean free path) plasma in the slab geometry, obtaining solutions valid through the sheath region. This paper reports the solution of the problem for the case of cylindrical geometry.

We consider the problem as formulated by Tonks and Langmuir[2] who wrote for the electron density a simple Boltzmann dependence

$$n_e(r) = n_o \exp(eV(r)/kT) \tag{1}$$

and for the ion generation a term proportional to the electron density

$$S(r) = \alpha\, n_e(r) \tag{2}$$

where $V(r)$ is the electric potential and n_o is the axial electron density.

The ion density at any radius is then given by an integral of the source function

$$n_i(r) = \int_0^r \frac{S(\rho)\,\frac{\rho}{r}\,d\rho}{\sqrt{\frac{2e}{m_i}\,[V(\rho) - V(r)]}} \quad . \tag{3}$$

Combining equations 1 and 3 with the Poisson equation

$$\nabla^2 V(r) = \frac{e}{\epsilon_o}(n_i - n_e)$$

and changing to the dimensionless variables

$$s = r \frac{\alpha}{\sqrt{\frac{2kT}{m_i}}} \qquad \eta = -\frac{eV(r)}{kT}$$

yields the equation governing the potential within the cylinder

$$\frac{1}{\beta^2}\left(s\frac{d^2\eta}{ds^2} + \frac{d\eta}{ds}\right) = \int_0^s \frac{e^{-\eta(\sigma)}\sigma\, d\sigma}{\sqrt{\eta(s) - \eta(\sigma)}} - s e^{-\eta(s)} \tag{4}$$

where $\beta^2 = \frac{2}{\alpha^2}\frac{n_o e^2}{m_i \epsilon_o}$.

Solutions to equation 4 were obtained numerically for the potential $\eta(s)$ and for the normalized electron density n_e/n_o for several values of the parameter β. Figure 1 shows the potential $\eta(s)$ with the location of the wall marked for several possible ion species. The location of the wall is determined by the condition that the current of electrons and ions be equal. The ion current is given by

$$J_i = \int_0^r S(\rho)\frac{\rho}{r}\, d\rho$$

while the electron current is assumed to be the flux from an electron gas with local density and a Maxwell-Boltzmann velocity distribution,

$$J_e = \frac{n_e}{2\sqrt{\pi}}\sqrt{\frac{2kT}{m_e}} .$$

Setting these two currents equal and changing to dimensionless form we have

$$\sqrt{\frac{m_i}{4\pi m_e}} = \exp\left(\eta(s_w)\right)\int_0^{s_w} \exp\left(-\eta(\sigma)\right)\frac{\sigma}{s_w}\, d\sigma \tag{5}$$

where s_w is the radius of the wall.

In Figure 2 the electron density for a mercury plasma is plotted against s/s_w for several values of the parameter β^2.

A quantity which is of interest in microwave experiments is the ratio of the zeroth to second moments of the electron density

$$\frac{\int_0^{r_w} n_e(r)\, r^3 dr}{\int_0^{r_w} n_e(r)\, r\, dr} = r_w^2 M \tag{6}$$

The number M is plotted as a function of β^2 in Figure 3.

At the end of the report are tabulated the potential, the electron density, and the first and second derivatives of the potential for several values of β^2. For values of $\beta^2 \geq 10^7$ one may use the table for $\beta^2 = \infty$ with an error of less than 0.3% except for the sheath which is less than 0.002 s_w thick for these values of β^2. At the end of each table is listed the value of s_w and the average electron density

$$\frac{\overline{n_e}}{n_o} = \frac{\int_0^{r_w} n_e(\rho)\rho\, d\rho}{\frac{1}{2} r_w^2 n_o}$$

for each ion species.

In attempting to compare this theory with experiment one should note that it is not necessary to know α. The value of β^2 can be calculated from

$$\beta^2 = 2\frac{n_o e^2}{m_1 \epsilon_o}\left(\frac{r_w}{s_w}\right)^2 = \frac{1}{s_w^2}\left(\frac{r_w}{\lambda_e}\right)^2$$

where $\lambda_e^2 = \dfrac{\epsilon_o kT_e}{n_o e^2}$ is the Debye length at the center of the cylinder.

I wish to express my appreciation to Prof. R. W. Gould for suggesting this problem and to the Office of Naval Research and the National Science Foundation for supporting the research.

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1. S. A. Self and G. S. Kino, Bull. Am. Phys. Soc. 7, 631 (1962)
2. L. Tonks and I. Langmuir, Phys. Review 34 (1929).

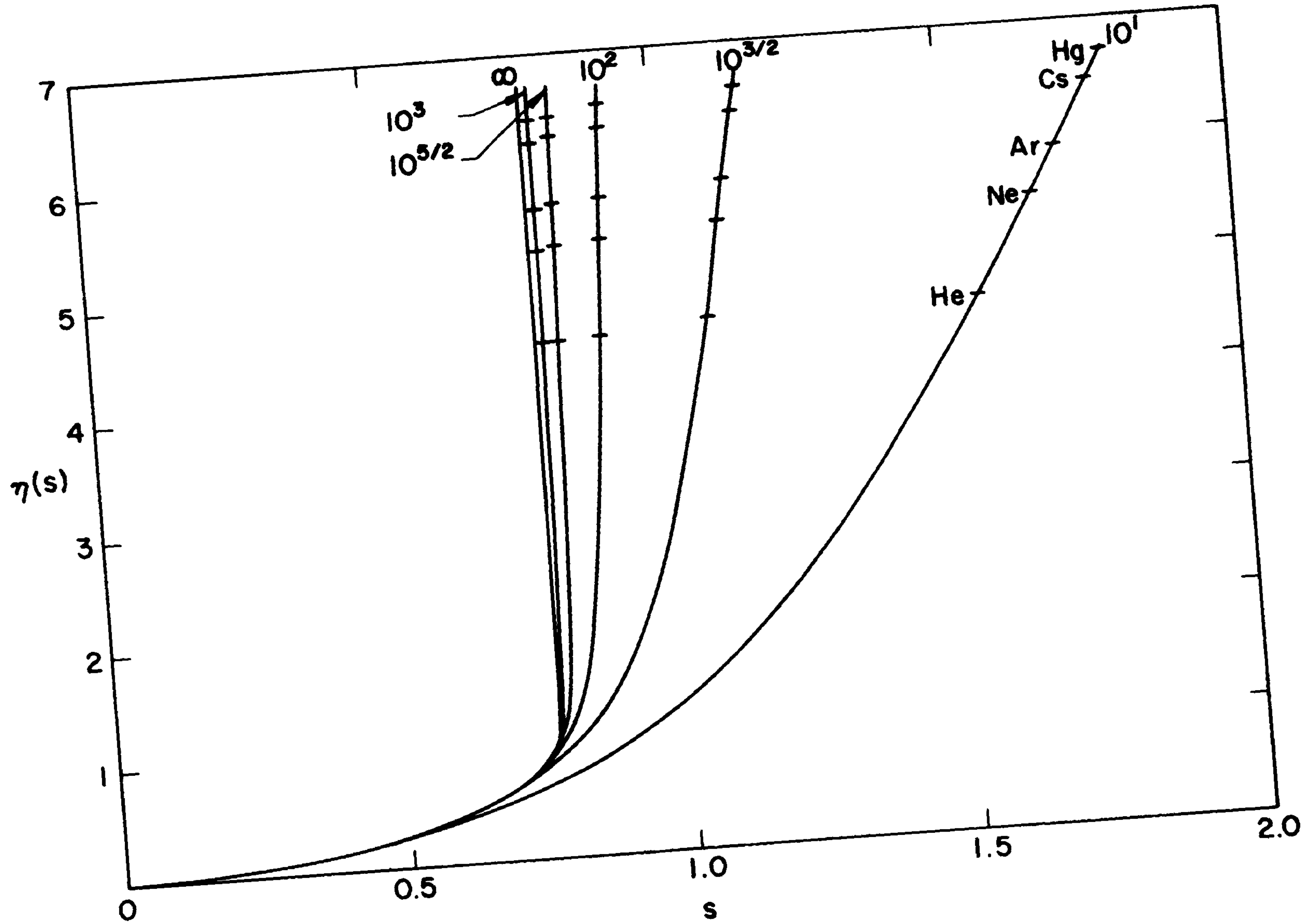

Fig. I Potential Function for Several Values of β

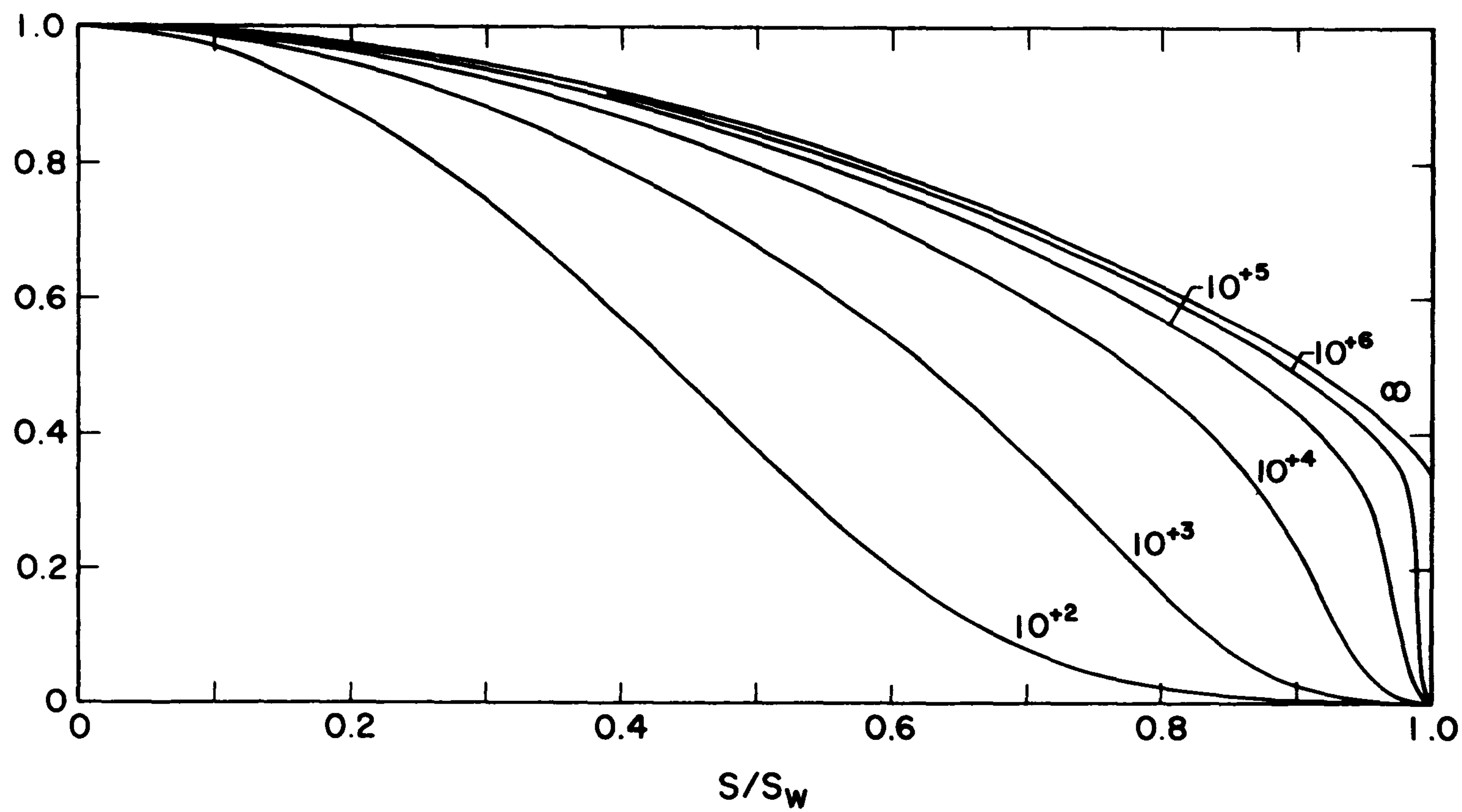

Fig. 2: Electron Density for Mercury Plasma

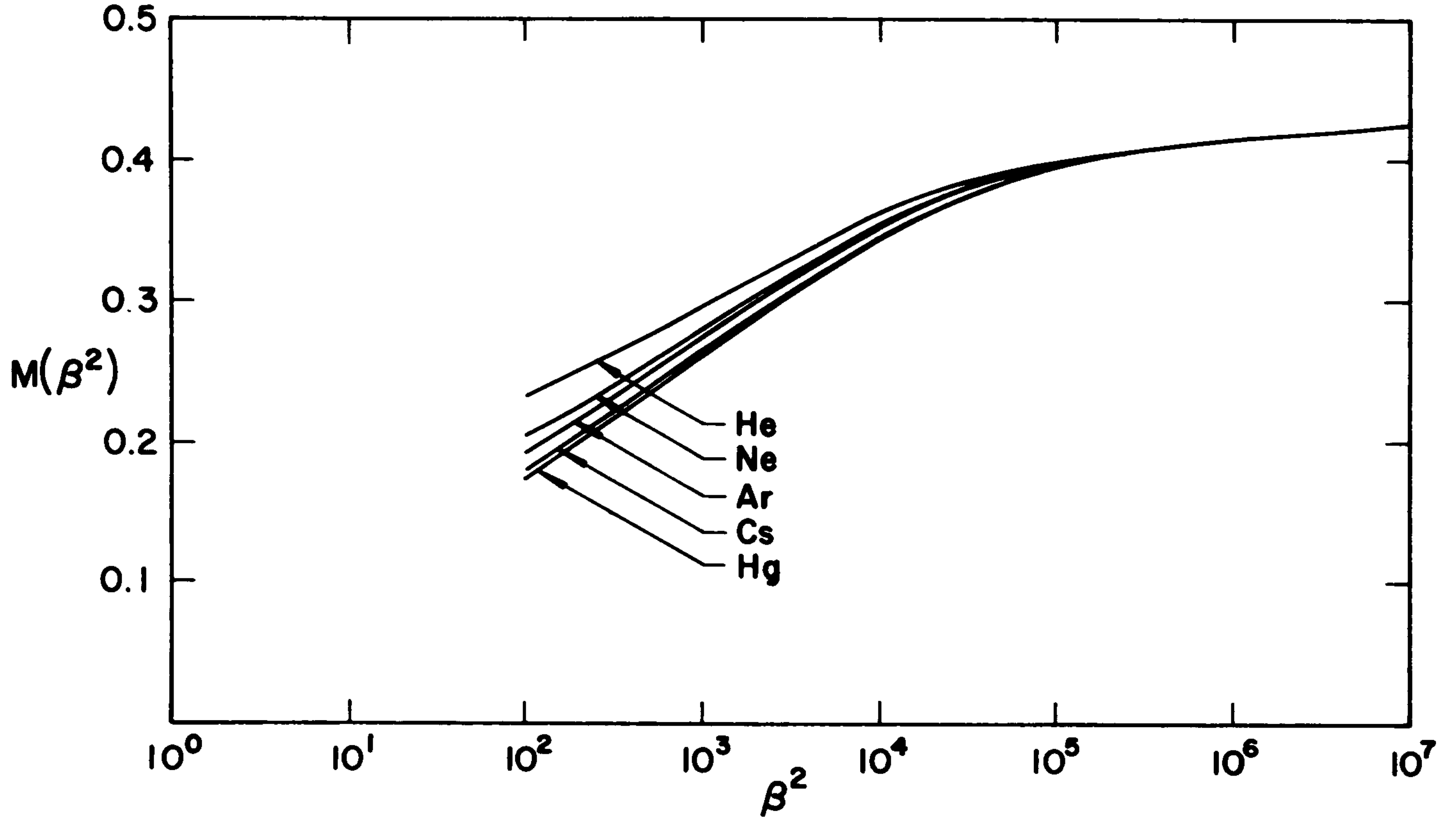

Fig. 3 Ratio of Second to Zeroth Moment of the Electron Density

$\beta^2 = \infty$

s	$\eta(s)$	$n(s)/n_o$	$\eta'(s)$	$\eta''(s)$
0.00	0.0000	1.0000	0.0000	2.000
0.05	0.0025	0.9975	0.1002	2.012
0.10	0.0100	0.9900	0.2016	2.049
0.15	0.0227	0.9776	0.3056	2.113
0.20	0.0407	0.9602	0.4135	2.210
0.25	0.0641	0.9379	0.5271	2.344
0.30	0.0935	0.9107	0.6487	2.532
0.35	0.1292	0.8788	0.7812	2.784
0.40	0.1719	0.8421	0.9288	3.142
0.45	0.2224	0.8006	1.0974	3.636
0.50	0.2821	0.7542	1.2968	4.385
0.55	0.3529	0.7027	1.5436	5.592
0.60	0.4378	0.6455	1.8698	7.689
0.65	0.5424	0.5814	2.3490	$1.207\ 10^1$
0.70	0.6787	0.5073	3.2105	$2.513\ 10^1$
0.75	0.8901	0.4106	6.0337	$1.378\ 10^2$
0.76	0.9598	0.3830	8.2056	$3.229\ 10^2$
0.77	1.0790	0.3399	$1.9443\ 10^1$	$2.579\ 10^3$

Ion Species	He	Ne	Ar	Cs	Hg
s_{wall}	0.772	0.772	0.772	0.772	0.772
$\frac{\overline{n}_e}{n_o}$	0.698	0.698	0.698	0.698	0.698

$\beta^2 = 10^6$

s	$\eta(s)$	$n(s)/n_o$	$\eta'(s)$	$\eta''(s)$
0.00	0.0000	1.0000	0.0000	2.000
0.05	0.0025	0.9975	0.1002	2.012
0.10	0.0100	0.9900	0.2016	2.049
0.15	0.0227	0.9776	0.3056	2.113
0.20	0.0407	0.9602	0.4135	2.210
0.25	0.0641	0.9379	0.5271	2.344
0.30	0.0935	0.9107	0.6487	2.530
0.35	0.1292	0.8788	0.7812	2.785
0.40	0.1719	0.8421	0.9287	3.139
0.45	0.2224	0.8006	1.0974	3.642
0.50	0.2821	0.7541	1.2967	4.388
0.55	0.3529	0.7027	1.5435	5.582
0.60	0.4378	0.6455	1.8696	7.689
0.65	0.5423	0.5814	2.3487	$1.210\ 10^1$
0.70	0.6787	0.5073	3.2089	$2.504\ 10^1$
0.75	0.8897	0.4108	5.9958	$1.336\ 10^2$
0.76	0.9585	0.3835	8.0304	$2.944\ 10^2$
0.77	1.0649	0.3447	$1.4897\ 10^1$	$1.288\ 10^3$
0.78	1.6740	0.1875	$1.9035\ 10^2$	$5.016\ 10^4$
0.79	7.8272	0.0004	$1.0861\ 10^3$	$9.580\ 10^4$

Ion Species	He	Ne	Ar	Cs	Hg
s_{wall}	0.787	0.788	0.788	0.788	0.789
$\frac{\overline{n}_e}{n_o}$	0.681	0.679	0.679	0.679	0.678

$$\beta^2 = 10^5$$

s	$\eta(s)$	$n(s)/n_o$	$\eta'(s)$	$\eta''(s)$
0.00	0.0000	1.0000	0.0000	2.000
0.05	0.0025	0.9975	0.1002	2.012
0.10	0.0100	0.9900	0.2016	2.049
0.15	0.0227	0.9776	0.3055	2.113
0.20	0.0407	0.9602	0.4134	2.209
0.25	0.0641	0.9379	0.5271	2.344
0.30	0.0935	0.9107	0.6487	2.528
0.35	0.1292	0.8788	0.7811	2.786
0.40	0.1719	0.8421	0.9286	3.136
0.45	0.2224	0.8006	1.0971	3.640
0.50	0.2821	0.7542	1.2964	4.383
0.55	0.3528	0.7027	1.5429	5.577
0.60	0.4377	0.6455	1.8685	7.663
0.65	0.5421	0.5815	2.3457	$1.203 \; 10^1$
0.70	0.6782	0.5076	3.1961	$2.458 \; 10^1$
0.75	0.8859	0.4124	5.7419	$1.099 \; 10^2$
0.76	0.9500	0.3867	7.2123	$1.918 \; 10^2$
0.77	1.0346	0.3554	$1.0057 \; 10^1$	$3.998 \; 10^2$
0.78	1.1638	0.3123	$1.6805 \; 10^1$	$1.026 \; 10^3$
0.79	1.4109	0.2439	$3.5808 \; 10^1$	$3.006 \; 10^3$
0.80	1.9892	0.1368	$8.7328 \; 10^1$	$7.630 \; 10^3$
0.81	3.3160	0.0363	$1.8502 \; 10^2$	$1.170 \; 10^4$
0.82	5.7393	0.0032	$2.9878 \; 10^2$	$1.066 \; 10^4$

Ion Species	**He**	**Ne**	**Ar**	**Cs**	**Hg**
s_{wall}	0.816	0.819	0.820	0.822	0.822
$\dfrac{\overline{n}_e}{n_o}$	0.648	0.643	0.641	0.638	0.637

$\beta^2 = 10^4$

s	$\eta(s)$	$n(s)/n_o$	$\eta'(s)$	$\eta''(s)$
0.00	0.0000	1.0000	0.0000	2.000
0.05	0.0025	0.9975	0.1001	2.010
0.10	0.0100	0.9900	0.2014	2.047
0.15	0.0227	0.9776	0.3053	2.111
0.20	0.0406	0.9602	0.4131	2.207
0.25	0.0641	0.9379	0.5266	2.340
0.30	0.0934	0.9108	0.6480	2.524
0.35	0.1291	0.8789	0.7802	2.777
0.40	0.1717	0.8422	0.9272	3.127
0.45	0.2221	0.8008	1.0951	3.623
0.50	0.2817	0.7545	1.2931	4.351
0.55	0.3522	0.7031	1.5371	5.508
0.60	0.4366	0.6462	1.8571	7.495
0.65	0.5402	0.5826	2.3174	$1.142 \; 10^1$
0.70	0.6734	0.5100	3.0918	$2.123 \; 10^1$
0.75	0.8643	0.4213	4.8258	$5.646 \; 10^1$
0.76	0.9157	0.4002	5.4696	$7.305 \; 10^1$
0.77	0.9744	0.3774	6.3123	$9.665 \; 10^1$
0.78	1.0429	0.3524	7.4397	$1.305 \; 10^2$
0.79	1.1245	0.3248	8.9755	$1.790 \; 10^2$
0.80	1.2243	0.2940	$1.1094 \; 10^1$	$2.478 \; 10^2$
0.81	1.3491	0.2595	$1.4025 \; 10^1$	$3.426 \; 10^2$
0.82	1.5084	0.2212	$1.8048 \; 10^1$	$4.668 \; 10^2$
0.83	1.7147	0.1800	$2.3450 \; 10^1$	$6.179 \; 10^2$
0.84	1.9828	0.1377	$3.0443 \; 10^1$	$7.832 \; 10^2$
0.85	2.3290	0.0974	$3.9059 \; 10^1$	$9.386 \; 10^2$
0.86	2.7685	0.0628	$4.9056 \; 10^1$	$1.055 \; 10^3$
0.87	3.3130	0.0364	$5.9934 \; 10^1$	$1.112 \; 10^3$
0.88	3.9681	0.0189	$7.1066 \; 10^1$	$1.105 \; 10^3$
0.89	4.7333	0.0088	$8.1885 \; 10^1$	$1.050 \; 10^3$
0.90	5.6034	0.0037	$9.2007 \; 10^1$	$9.691 \; 10^2$
0.91	6.5705	0.0014	$1.0126 \; 10^2$	$8.798 \; 10^2$

Ion Species	He	Ne	Ar	Cs	Hg
s_{wall}	0.888	0.897	0.901	0.908	0.910
$\frac{\overline{n_e}}{n_o}$	0.574	0.562	0.557	0.550	0.547

$$\beta^2 = 10^3$$

s	$\eta(s)$	$n(s)/n_o$	$\eta'(s)$	$\eta''(s)$
0.00	0.0000	1.0000	0.0000	1.984
0.05	0.0025	0.9975	0.0994	1.996
0.10	0.0100	0.9901	0.2000	2.031
0.15	0.0225	0.9777	0.3029	2.092
0.20	0.0403	0.9605	0.4097	2.183
0.25	0.0636	0.9384	0.5218	2.310
0.30	0.0926	0.9115	0.6413	2.482
0.35	0.1279	0.8800	0.7709	2.715
0.40	0.1699	0.8437	0.9140	3.032
0.45	0.2196	0.8028	1.0756	3.464
0.50	0.2779	0.7574	1.2630	4.076
0.55	0.3465	0.7072	1.4875	4.966
0.60	0.4276	0.6521	1.7671	6.322
0.65	0.5246	0.5918	2.1329	8.490
0.70	0.6432	0.5256	2.6394	1.209 10^{1}
0.75	0.7925	0.4527	3.3854	1.832 10^{1}
0.80	0.9886	0.3721	4.5452	2.901 10^{1}
0.85	1.2585	0.2841	6.3932	4.607 10^{1}
0.90	1.6448	0.1931	9.2490	6.875 10^{1}
0.95	2.2027	0.1105	1.3249 10^{1}	9.014 10^{1}
1.00	2.9834	0.0506	1.8059 10^{1}	9.964 10^{1}
1.05	4.0098	0.0181	2.2947 10^{1}	9.367 10^{1}
1.06	4.2440	0.0144	2.3870 10^{1}	9.108 10^{1}
1.07	4.4871	0.0112	2.4767 10^{1}	8.822 10^{1}
1.08	4.7392	0.0087	2.5634 10^{1}	8.514 10^{1}
1.09	4.9997	0.0067	2.6469 10^{1}	8.196 10^{1}
1.10	5.2685	0.0052	2.7272 10^{1}	7.868 10^{1}
1.11	5.5451	0.0039	2.8042 10^{1}	7.534 10^{1}
1.12	5.8292	0.0029	2.8779 10^{1}	7.203 10^{1}
1.13	6.1205	0.0022	2.9482 10^{1}	6.875 10^{1}
1.14	6.4188	0.0016	3.0154 10^{1}	6.556 10^{1}

Ion Species	He	Ne	Ar	Cs	Hg
s_{wall}	1.075	1.107	1.119	1.140	1.147
$\frac{\overline{n}_e}{n_o}$	0.445	0.420	0.411	0.396	0.392

$\beta^2 = 10^2$

s	$\eta(s)$	$n(s)/n_o$	$\eta'(s)$	$\eta''(s)$
0.00	0.0000	1.0000	0.0000	1.860
0.05	0.0023	0.9977	0.0931	1.867
0.10	0.0093	0.9907	0.1870	1.891
0.15	0.0210	0.9792	0.2825	1.932
0.20	0.0376	0.9631	0.3805	1.991
0.25	0.0591	0.9426	0.4819	2.071
0.30	0.0859	0.9177	0.5879	2.172
0.35	0.1180	0.8887	0.6995	2.301
0.40	0.1560	0.8556	0.8183	2.460
0.45	0.2000	0.8187	0.9459	2.652
0.50	0.2507	0.7782	1.0841	2.887
0.55	0.3086	0.7344	1.2353	3.170
0.60	0.3745	0.6876	1.4019	3.507
0.65	0.4491	0.6382	1.5869	3.908
0.70	0.5336	0.5865	1.7934	4.374
0.75	0.6289	0.5332	2.0251	4.906
0.80	0.7365	0.4788	2.2848	5.502
0.85	0.8579	0.4240	2.5760	6.154
0.90	0.9947	0.3698	2.9004	6.840
0.95	1.1485	0.3171	3.2590	7.518
1.00	1.3212	0.2668	3.6510	8.158
1.05	1.5141	0.2200	4.0723	8.710
1.10	1.7288	0.1775	4.5186	9.120
1.15	1.9662	0.1400	4.9806	9.358
1.20	2.2270	0.1078	5.4505	9.418
1.25	2.5112	0.0812	5.9175	9.268
1.30	2.8186	0.0597	6.3724	8.926
1.35	3.1481	0.0429	6.8060	8.434
1.40	3.4987	0.0302	7.2120	7.838
1.45	3.8688	0.0209	7.5861	7.182
1.50	4.2568	0.0142	7.9265	6.467
1.55	4.6608	0.0095	8.2309	5.782
1.60	5.0794	0.0062	8.5021	5.096
1.65	5.5103	0.0040	8.735	4.441
1.70	5.9524	0.0026	8.940	3.755
1.75	6.4038	0.0016	9.100	3.100

Ion Species	He	Ne	Ar	Cs	Hg
s_{wall}	1.548	1.649	1.693	1.758	1.787
$\dfrac{\overline{n_e}}{n_o}$	0.299	0.264	0.250	0.232	0.225

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